EXAMINING DRIVER'S EYE-MOVEMENTS AND COGNITIVE WORKLOAD: AN EXPLORATORY STUDY USING ELECTROOCULOGRAPHY

by

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ABSTRACT

Previous research has suggested a link between cognitive workload and gaze concentration. As mental workload increases, humans begin to stare straight ahead. If drivers' scanning behaviors are attenuated as a result of secondary in-vehicle tasks, then their situation awareness and their ability to react to unpredictable events may be impaired. Using video-based eye tracking technology in a naturalistic setting is notoriously difficult; however, electrooculography (EOG) may provide a reliable, real-time measure of changes in visual scanning under manipulated levels of cognitive workload. This study assessed the viability of EOG to measure changes in scanning behavior when drivers performed common in-vehicle tasks while driving an automobile. Notably, EOG measures were not sensitive to driver's workload, but instead demonstrated that speech production inherent to a task contributes to an additive effect in identified eye movements.

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INTRODUCTION

Humans cannot attend to a region's visual information unless we look at that region (Hoffman & Subramaniam, 1995), even though we often look at a region without processing the visual information (i.e., inattention blindness; Simons & Chabris, 1999; Strayer, Drews, & Johnston, 2003; Taylor et al., 2013). These issues are relevant to driving because how the eyes scan the driving environment directly influences drivers' ability to respond to the real time demands of operating a motor vehicle. If secondary-task activities that drivers perform affect visual scanning behavior, then the wisdom of performing those secondary-to-driving tasks should be reconsidered.

Cognitive Distractions in the Vehicle

Obvious forms of distraction occur when drivers are glancing away from the road to read printed directions or when they remove their hands from the wheel to return a text message. In 2010, over 416,000 individuals were injured and 3,092 were killed in crashes due to distracted driving (National Highway Traffic Safety Administration [NHTSA], September, 2012). Regan, Hallet, and Gordon (2011) define *driver distraction* as a subset of *driver inattention* that occurs when attention is diverted away from the task of driving toward a nondriving secondary task, all to the detriment of safe driving.

One source of distraction is that of cognitive distraction induced by performing tasks that are mentally demanding. Sirevaag et al. explain that this source occurs when an individual faces the "cost of performing one task in terms of a reduction in the capacity to perform additional tasks, given that the two tasks overlap in their resource demands" (1993, p. 1121). With this form of distraction, drivers' eyes can be on the roadway and their hands on the wheel; however, their minds are not actively processing the incoming information. In this case, attention has been directed to processing the internal information associated with the secondary task instead of the driving environment (Recarte & Nunes, 2000). Strayer and Drews (2007) describe the concept of inattentional blindness that can occur as a result of drivers engaging in cellphone conversations. While drivers have their hands on the steering wheel and eyes on the road, their ability to process information in their environment is reduced by the attentional demands of talking on a cell phone. This cognitive source of distraction is much more difficult to study because the typical outward signs of distraction are often missing. The driver appears to be looking ahead at the roadway with both hands on the wheel, but their ability to perceive, process, and predict changes in their surroundings is reduced (Muhrer & Vollrath, 2011, p. 557).

The ability to perceive, process, and predict one's surroundings has been defined as situation awareness. Using the acronym SPIDER, Fisher and Strayer (2014) delineate the processes necessary for a driver to maintain this alert state. The crucial first step is a driver's **S**canning of their environment, followed by **P**redicting possible changes and **I**dentifying ongoing hazards in the environment. Lastly, situation awareness requires drivers to be able to utilize this processed information to **D**ecide and then **E**xecute their selected **R**esponse. If the driver is not able to perform these processes due to the cognitive demand of a secondary task, their ability to safely navigate their vehicle is impaired: in effect, they have become distracted.

With the number of electronic devices currently available in the vehicle resulting in more varied forms of communication, the potential sources of driver distraction are growing rapidly. How might we assess cognitive distraction when drivers perform non-driving secondary tasks, such as conversing on a phone or interacting with auditory messaging services— tasks that drivers are beginning to perform with regularity? When are drivers' attentional capacities overloaded and their ability to safely operate a vehicle impaired? The need for clearly understanding cognitive distraction has never been greater, especially given that automotive giants, such as Ford Motor Company, claim that having "eyes on the road, hands on the wheel" is sufficient for safely operating a motor vehicle (Levin, 2011). In fact, when NHTSA published their driver distraction guidelines in the federal register (2012), they stated that these guidelines currently apply to manual and visual sources of distraction *because* "it is far less clear how to measure the level of cognitive distraction" (NHTSA, 2012, p. 22). Because research on cognitive distraction is ongoing, industry developers are taking advantage of the absence of knowledge in this area and are developing auditory systems low in visual or manual interaction demands without fully vetting the system's mental demand. Mental workload's links to cognitive distraction must be better clarified in order to inform the development and application of in-vehicle technology.

Cognitive Workload and Gaze Concentration

However, measuring cognitive distraction is challenging because one cannot look at a driver and determine if they are cognitively overloaded. One promising methodology is to examine how drivers' visual scanning behavior changes under cognitive load. If a direct link between visual scanning and mental workload is identified, then we may understand how auditory secondary tasks alter drivers' processing of their environment. This link is being explored by research on the visual tunneling phenomenon, also called gaze concentration (Dirkin, 1983). Gaze concentration is so called because individuals under cognitive workload have been shown to stare straight ahead, making fewer saccades to the peripheral (Engström, Johansson, & Östlund, 2005; Harbluk, Noy, Trbovich, & Eizenman, 2007; He, Becic, Lee, & McCarley, 2011; Rantanen & Goldberg, 1999; Recarte & Nunes, 2000; Reimer, 2009; Reimer, Mehler, Wang, & Coughlin, 2012; Victor, Harbluk, & Engström, 2005). In fact, in Figure 1 from a driving and eye-tracking study conducted by Reimer (2009), we can clearly observe a concentration of gaze as cognitive workload increased. Figure 1a displays the spread of gaze during a pretask baseline while Figures 1b, c, and d demonstrate the decreased spread of gaze as 0-back, 1-back, and 2-back tasks are performed, respectively. While the gaze concentration differences between the increased levels of workload did not significantly differ from each other, they did differ from the single task driving condition.

If drivers' hands are on the steering wheel and their eyes are on the road, why should their eye movements change under cognitive workload? Gaze concentration is thought to occur not as a sensory decrease; instead, Dirkin and Hancock (1985) argue that as cognitive workload increases, the fact that an individual's functional visual field narrows is due to selective attending rather than to a sensory decrease. Additionally, Cooper, Medeiros-Ward, and Strayer (2013) dissociated the influence of eye movements and cognitive workload on lane deviation. Their research demonstrated that cognitive workload, rather than eye movements, was the proximal cause of reduced standard deviation of lane position. These two lines of research reflect the idea that cognitive workload appears to be a causal factor in changing drivers' behaviors as seen in how they scan their environment.

Manipulated levels of cognitive workload have been used in many studies to demonstrate this concentration of gaze that narrows in direct relation to the difficulty of the cognitive task (Harbluk et al., 2007; Reimer et al., 2012). However, these studies compared baseline driving to a limited number of conditions in which mental workload was increased. On the other hand, in a series of four studies, May, Kennedy, Williams, and Dunlap (1990) found significantly different degrees of gaze concentration in a laboratory free-viewing task as workload increased. A wider range of cognitive workload when driving a real vehicle needs to be examined (Recarte & Nunes, 2000).

With scanning behaviors reduced by cognitive workload, drivers' ability to process relevant driving cues and unexpected events is impaired. However, even if there are minimal differences in cognitively loaded scanning behaviors, there still remains the possibility of inattention blindness whereby individuals may "look" at environmental content without "seeing" or processing that information (Reyes & Lee, 2008; Strayer et al., 2003; Strayer & Drews, 2007; Strayer, Watson, & Drews, 2011). Scanning patterns are crucial to navigating a vehicle through the real world, but the information must be attended to in order for it to be acted upon (cf. SPIDER, Fisher & Strayer, 2014): if attention is not allocated to the external information, then it cannot be realized (Recarte & Nunes, 2000, p. 31).

Eye Tracking Limitations in Gaze Concentration

Until now, gaze concentration has been measured in naturalistic settings via invasive head-mounted (Bulling, Ward, Gellersen, & Troster, 2011) or expensive dash mounted eye trackers and software (Taylor et al., 2013). Using eye tracking equipment, a few researchers have been able to measure changes in eye movements due to manipulated cognitive workload (Reimer, 2009; Reimer et al., 2012; Victor et al., 2005). However, eye tracking technology faces limitations in the field due to environmental conditions such as glare, participant's use of eyeglasses or contacts, the discomfort from wearing the device for extended periods, and the restriction of free movement (Joyce, Gorodnitsky, King, & Kutas, 2002; Taylor et al., 2013). The use of video to manually code eye movements also faces similar environmental constraints, such as glare or loss of calibration due to head movements, in addition to its scoring being tedious and time-consuming.

The Poor Man's Solution: Electrooculography

Electrooculography (EOG) may provide a noninvasive, economical method for tracking changes in eye movements between various conditions (Bulling et al., 2011; Joyce et al., 2002; Koga & Osaka, 1983; Woestenburg, Verbaten, & Slangen, 1984). EOG is a measurement of the changes in the electrical potential field that occur when the eye moves either horizontally or vertically (Bulling et al., 2011; Luck, 2005). Of particular interest is horizontal EOG (hEOG), which is sensitive to the scanning behavior of the participant. These horizontal glances are necessary for drivers to anticipate changes in their driving environment (Taylor et al., 2013). EOG has been used successfully to trace eye movements during reading (Fisher & Rothkopf, 1982), has implications for wheelchair control, and can provide an interface for disabled persons to access and control computer programs (Merino, Rivera, Gomez, Molina, & Dorronzoro, 2010).

EOG has even been successfully matched to participants' gaze locations in a controlled laboratory study (Joyce et al., 2002). Joyce and colleagues mapped participants' glances to x, y coordinates on a screen, but only after extensive calibrations and with the use of a bite board to stabilize participants' head movements. Encouragingly, Koga and Osaka concluded that EOG was the best option when compared to corneal reflection methods (1983, p. 189). They added that EOG can measure eye movements when a stabilizing bite board is not feasible, such as when infants are the subject of interest. Although specific coordinates might not be attainable, hEOG has the potential to track real-time changes in continuous eye movements within a naturalistic driving setting.

Applying EOG to the Field

This study proposes to examine hEOG collected from an on-road study that examined realistic, in-vehicle tasks that are commonly performed by drivers today (cf. Strayer et al., in press). Recarte and Nunes (2000) described the need for more tasks to be studied while driving. Researchers over the past decade have risen to this challenge by manipulating drivers' cognitive workload and measuring changes in visual scanning patterns to give support to the gaze concentration hypothesis (Harbluk et al., 2007;

Reimer, 2009; Reimer et al., 2012; Victor et al., 2005). However, this body of previous work has used surrogate tasks to manipulate cognitive workload, such as auditory working memory tasks (n-back task, Reimer et al., 2012; counting *n* number of targets, Victor et al., 2005). Following the lead of Greenberg and colleagues (2003), we sought to assess driver distraction in terms of *current* in-vehicle activities. hEOG could turn out to be the “poor man’s” solution in terms of cost, usability, and noninvasive measures to assess the cognitive distraction potential of various tasks within a wide variety of contexts.

Within the framework of the gaze concentration hypothesis and because eye tracking technology is problematic when used in naturalistic settings, our goal is to assess whether hEOG would be sensitive to the changes in eye movements that occur under varying cognitive workload. The tasks to be examined in this study were carefully selected to represent a broad range of activities that are being performed while driving and that provide a range of cognitive load. The collection of eye movement data remained constant across each of these conditions. Beginning with single-task driving to provide a baseline of performance, mental workload is hypothesized to increase as participants listen to the radio or an audio book excerpt, talk with a passenger, and then converse on a handheld cellphone and handsfree device. Participants received brief training before performing the final two tasks. Participants interacted with a text to speech messaging system to send and receive text and email messages, and completed the Operation Span Task (OSPAN; Engle, 2002).

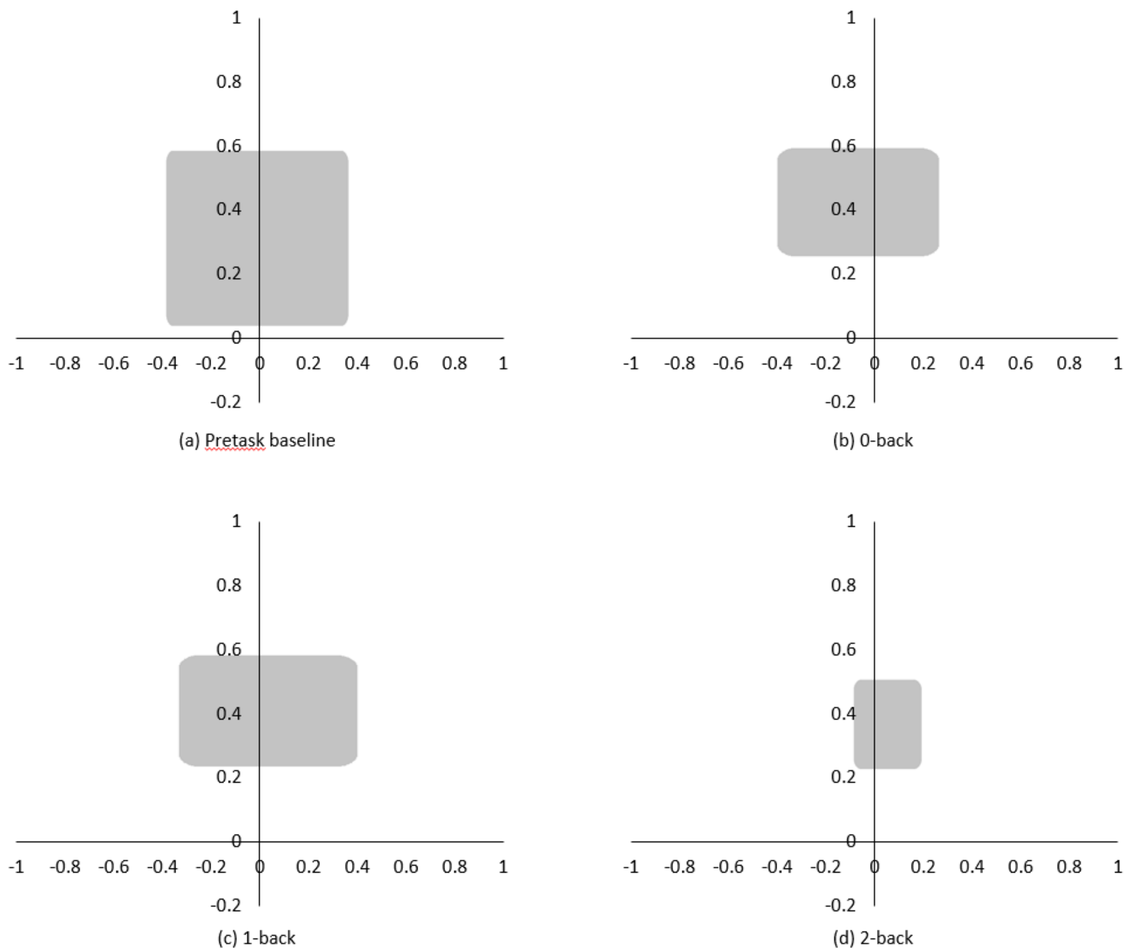

Figure 1. Gaze distribution for (a) pretask baseline, (b) 0-back, (c) 1-back, and (d) 2-back (adapted from Reimer, 2009).

PURPOSE OF CURRENT RESEARCH

The purpose of this research is to develop a method to systematically assess changes in eye movements while driving as cognitive workload was manipulated. To this end, we propose two Aims as discussed below.

Aim 1

By combining the concept of gaze concentration and the utility of hEOG as described in previous research, we wish to examine the effectiveness of hEOG in detecting changes in eye movements amongst a wide variety of realistic in-vehicle tasks.

Aim 2

Our prior research has focused on the use of cellphones while driving (Cooper & Strayer, 2008; Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Strayer, Drews, Albert, Johnston, 2001; Strayer & Drews, 2004;). However, each of these studies has used different measurements, procedures, and populations across the past decade. Not only has the technology advanced within that time, but so has the way in which we use our cellphones while driving (GPS, SIRI, handsfree communication, etc.). Because of the difficulty in assessing cognitive distraction, understanding how mental workload affects one's scanning behavior across various tasks will enable consumers to make more informed decisions when choosing what activities to perform while driving. Moreover, as Strayer, Watson, and Drews suggest, any new devices that are to be installed in vehicles should first be vetted for their “distraction potential” to the driver (2011, p. 56). Thus, we wish to assess the effects of the described activities on gaze concentration in a realistic driving environment.

METHODS

Participants

Thirty-five participants (14 men and 21 women) from the University of Utah participated in the experiment. Participants ranged in age from 18 to 33, with an average age of 23.8 years. All reported normal neurological functioning, normal or corrected-to-normal visual acuity, normal color vision (Ishihara, 1993), a valid driver's license, and were fluent in English. Participants' years of driving experience ranged from 2 to 17, with an average of 7.4 years. All participants owned a cellular phone and 94% reported that they used their phone regularly while driving. They were recruited via university approved flyers posted on campus bulletin boards and via word of mouth within the community. Interested individuals contacted an e-mail address for further information and to schedule an appointment.

Materials

The OSPAN task, developed by Engle (2002), creates a challenging dual-task condition. Participants completed an auditory version of the OSPAN in which they attempted to recall single syllable words in serial order while solving mathematical problems. The OSPAN is thought to require executive attention (Watson & Strayer, 2010) and is considered to be an attentionally demanding task. In the auditory OSPAN task, participants were asked to remember a series of two to five words that are interspersed with math-verification problems (e.g., given "[3 / 1] – 1 = 2?" – "cat" – "[2 x 2] + 1 = 4?" – "box" – RECALL, the participant should have answered "true" and "false" to the math problems when they were presented and recalled "cat" and "box" in the order in which they were presented when given the recall probe).

Equipment

The study used an instrumented 2010 Subaru Outback. The vehicle was augmented with four 1080p LifeCam USB cameras that captured the driving environment and participants' facial features.

A Neuroscan 32-electrode channel QuikCap was connected to a NuAmp amplifier. Hosted on a research laptop, Neuroscan 4.5 software was used to collect continuous EOG from the NuAmp amplifier throughout each condition.

Cellular service was provided by Sprint. The cellular phone was manufactured by Samsung (Model M360) and the handsfree earpiece was manufactured by Jawbone (Model Era). Participants dialed a friend or family member and the volume for both the cellular phone and the handsfree earpiece was adjusted prior to driving.

NaturalReader 10.0 software was used to simulate an interactive messaging service with text to speech features. Participants indicated names of friends prior to beginning the study that were then entered into a template containing generic e-mail and text messages (e.g., "Text from Alice. 'Hey! Let's meet for lunch sometime this week. When are you free?'"). Participants were given a short list of commands that must be used in order for the messaging program to respond. The NaturalReader program was controlled by the experimenter who reacted to the participants' verbal commands, mimicking a speech detection system with perfect fidelity. If a participant did not use the correct command, the experimenter would not allow the NaturalReader program to continue, but would wait for the participant to give the correct command.

Procedure

Prior to their appointment time, participants were sent the Informed Consent form, general demographic surveys, and instructions for completing the 20 minute online defensive driving course and the certification test. Prior to participation, the Division of Risk Management Department at the University of Utah ran a Motor Vehicles Record (MVR) report on each prospective participant to ensure participation eligibility based on a clean driving history (e.g., no at-fault accidents in the past 5 years or history of traffic violations). In addition, following university policy, each prospective participant was required to complete a university devised 20-minute online defensive driving course and pass the certification test.

Upon arrival at the lab in the Behavioral Sciences building, the research team placed Ag/AgCl-sintered EOG electrodes on the participant and ensured that impedances were on average below 10kΩ. A reference electrode was placed behind the left ear on the mastoid bone and electrode site FP1 served as the ground. The EOG electrodes were placed at the lateral canthi of both eyes (horizontal) and above and below the left eye (vertical) to track eye movements and record eye blinks. Participants' field of view and normal range of motion were not impeded when wearing the electrodes.

Before beginning the study, the driver was familiarized with the controls of the instrumented vehicle, adjusted the mirrors and seat, and was informed of the tasks to be completed while driving. The participant drove around a parking lot in order to become familiar with the handling of the vehicle. Next, participants drove one circuit on a 2.75 mile loop in the Avenues of Salt Lake City, UT in order to become familiar with the route itself. The route provided a suburban driving environment and contains nine all-way controlled stop signs, one two-way stop sign, and two stoplights. A research assistant and an experimenter accompanied the participant in the vehicle at all times. The research assistant sat in the rear and the experimenter was in the front passenger seat in order to have ready access to the redundant braking system and to notify the driver of any potential roadway hazards.

The driver's task was to follow the route defined above while complying with all local traffic rules, including a 25 mph speed restriction. Throughout each condition, continuous EOG was collected. Each condition lasted approximately 9 minutes, which is the equivalent of one loop around the track. At the conclusion of the study, participants returned to the Behavioral Sciences building where the EOG electrodes were removed and the participants were compensated for their time and debriefed.

Participants were asked to complete eight distinct conditions that were chosen to provide a range of cognitive workload. These tasks were counterbalanced across participants using a balanced Latin square design. Presented in hypothesized ascending order of cognitive workload, single task driving was selected to provide a baseline of undistracted driving performance. Participants' attention was fully available for the task of driving.

In the second condition, participants were allowed to select a radio station to which they normally listen. They selected the station before beginning to drive and adjusted the volume to within a comfortable level. Once they begin driving, they were not allowed to change the station to avoid the influence of manual distraction on task demands.

In the third condition, participants chose an excerpt from three available audio books. They selected an excerpt from the first chapter of *The Giver* by Lois Lowry, the twentieth chapter from *Water for Elephants* by Sara Gruen, or the tenth chapter from *Harry Potter and the Sorcerer's Stone* by J. K. Rowling. Once again, all manual adjustments to volume were made before the driver began the loop. Participants were informed that at the end of the audio book, they would take a simple quiz about the events of their chosen audio book. This quiz was to ensure that participants attended to the story, and participants scored an average of 83%.

Conditions four through six focused on different forms of conversation. The fourth condition entailed conversation with the experimenter in the passenger seat. Participants indicated desired conversation topics at the beginning of the study. Experimenters asked the participant to start telling an interesting story from the list and then helped to maintain an engaging conversation for the duration of the drive by asking questions about the story or by responding with a story of their own.

The fifth condition required the participant to call a friend or family member and talk with that person on a handheld cellular phone. The call was initiated and the volume adjusted before the drive began to avoid the visual distraction that occurs when trying to dial a phone number or adjust volume. Due to the microswitch that was attached to left thumb, participants held the phone with their right hand. The majority of participants indicated that this was the hand they normally used when conversing on a cell phone.

Similarly, the sixth condition was a conversation with a friend or family member, but it occurred via our handsfree Bluetooth earpiece. Participants indicated in which ear they wished to use the handsfree earpiece. The adjustable earpiece was selected to fit the participant's unique ear size and shape, and then the volume of the call was adjusted before beginning the drive. Once again, the call was placed before the drive began.

For condition seven, the participant interacted with a text to speech program, NaturalReader 10.0, that simulated current e-mail and text messaging services. Participants did not know that they were interacting with a text-to-speech only program that was controlled by the research assistant in the back seat. The research assistant was trained to control the program as if it were an automated program that responded only to specific commands. Similar, full-use programs are now being regularly integrated into vehicles for the driver's use (e.g., Toyota's *Entune*, Ford's *Sync* and *MyFord Touch*). Prior to beginning to drive, the participant was familiarized with the program's basic commands, such as *Repeat*, *Reply*, *Forward*, *Delete*, and *Next Message*. The participant completed a simple tutorial so as to become familiar with how the commands functioned. Participants were asked to dictate responses to the messages as needed.

The final condition was expected to provide the greatest cognitive workload, that of solving simple math problems and remembering words. The OSPAN task requires participants to solve sets ranging from two to five math problems and remember as many words in serial order). Participants were given a short example of the OSPAN before beginning the drive.

Continuous EOG was collected throughout each condition. The EOG was amplified and recorded using NuAmps NeuroScan system, which was mounted in the backseat of the instrumented vehicle. The EOG was filtered online with a low pass filter of 50 Hz and a high pass set to DC with a sample A/D rate of 250. In addition to gain set at 19, a notch filter of 60 Hz was selected to attenuate surrounding electrical noise.

RESULTS

The presented data are a part of a larger dataset within this study procedure. The other dependent measures will not be detailed here, but made reference to in Strayer et al. (in press).

Using Neuroscan 4.5 Edit software, the hEOG was first cleaned, removing sections of visible environmental artifacts. Next, the individual left and right hEOG channels were combined and subsequent analysis applied to a single channel that encompassed both left and right eye movements. A band-pass, zero phase shift filter of .1 to 30 Hz was applied (Merino et al., 2010). An in-lab calibration of our system at visual angles of 3.5° and 8° combined with current literature recommendations resulted in the following parameters for saccade identification: a threshold function of ±100μV (Luck, 2005) was used to identify eye movements that exceeded a minimum horizontal visual angle of c. 6° with a refractory period of 200ms (cf. Bulling et al., 2011). The Edit software ascribed markers to each eye movement that met these parameters. The number of markers was then summed to give a total number of identified eye movements for each participant and each condition. Because the experimental conditions varied slightly in duration, we divided the total number of identified eye movements by the duration of that condition, resulting in a total number of eye movements per minute for each condition. The individual participant averages were then combined across participants for each of the eight conditions.

Descriptive statistics for the resulting eye movements per minute data, including the mean, standard deviation (SD), and standard error (SE), are presented in Table 1. Eye movements per minute, and all subsequent analyses, were analyzed using a Repeated Measures ANOVA with eight levels of workload. There was a significant main effect of workload, $F(7, 238) = 54.95$, $p < .001$, partial $\eta^2 = .62$ (see Figure 2). The significant mean differences of the number of eye movements per minute ($p < .05$) between the various workload conditions are presented in Table 2. Taken from the larger study of which the hEOG is a part, Figure 3 presents the cognitive distraction scale for each of the conditions as assessed by a series of dependent variables (Strayer, et al., in press). Clearly, the pattern identified by examining changes in hEOG does not match cognitive workload as assessed by the combined force of multiple other dependent measures. The eye movements change dependent upon the tasks, but not directly as a result of the task's cognitive workload. The significant main effect of condition appears to be linked to the amount of speech production that a task required rather than the task's assessed cognitive workload.

To ensure that the pattern seen in Figure 2 was not an artifact of the algorithms that the Edit software used to process the data, we conducted three additional analyses checks. First, we examined the standard deviation of the hEOG by exporting the cleaned data to MATLAB. If total scanning excursions to the peripheral were reduced, the range of the hEOG should reflect reduced variation as cognitive workload increased. After calculating the standard deviation for each condition by participant, we performed a Repeated Measures ANOVA with eight levels of workload. There was a significant main effect of condition, $F(7, 238) = 8.24$, $p < .001$, partial $\eta^2 = .20$, but the pattern seen in the previous eye movements per minute analysis was again confirmed (see Figure 4).

Secondly and in addition to the standard deviation analysis check that bypassed the Edit software, we performed a subsidiary fast Fourier transform (FFT) analysis that examined the spectral characteristics of the hEOG. This analysis does not make assumptions about the size or refractory periods of saccades; instead, FFT examines the energy distributed across the frequencies of eye movements. Energy, or power, is computed as the square of the average of the waveform's amplitude (Quantitative Electroencephalography, 2013, December 13). There was a significant main effect of workload, $F(7, 238) = 34.00$, $p < .001$, partial $\eta^2 = .50$ (see Figure 5). This methodology examined the same data as the eye movements per minute analysis, and provided a similar pattern as seen in Figures 2 and 4. What hEOG is measuring appears to be different from the cognitive workload measures seen in Figure 3. We can see that both the eye movements per minute in Figure 2 and the FFT analysis in Figure 5 have matching patterns showing greater activity in conditions that demanded speech production. Similarly, both of these analyses' patterns do not map onto the cognitive distraction scale seen in Figure 3.

However, because the pattern showed that the greatest eye movement activity occurred in conditions with speech production, we were concerned that hEOG was contaminated by, and merely a reflection of, muscle movement artifact. To control for the muscle movement during speech production, we also analyzed the spectral characteristics of electrode site A2, which was placed on the right mastoid behind the ear. By doing so, we were able to covary electrode A2's recorded muscle movements from the hEOG spectral distributions. There was a significant main effect of workload, *F*(7,

238) = 3.54, $p < .001$, partial $\eta^2 = .09$ (see Figure 6). Once again, a pattern similar to that as observed in the eye movement per minute counts and the initial FFT analyses was obtained, which again differs from the workload metric seen in Figure 3 but matches the patterns seen in Figures 2, 4, and 5.

We have already ruled out the fact that the pattern is a result of the analysis methods counting the number of eye movements per minute by conducting the FFT spectral analysis that provided the same pattern. Initial concerns that muscle movements from the jaw during talking conditions were allayed by the analysis of covariance for muscle movements, which resulted in this consistent pattern. However, since increased muscle movements in a naturalistic driving environment were a concern, we examined similar data from two separate environments in the third analysis check.

As mentioned before, the instrumented vehicle hEOG analyzed previously was from a third experiment in a larger study consisting of three experiments (Strayer et al., in press). In order to better understand the pattern that hEOG was reflecting, the third analysis check we performed was the same as described for the in-car eye movements per minute. In the first experiment from Strayer et al. (in press), participants performed the same eight tasks, but were seated in front of a stationary computer screen in lieu of driving a vehicle. Participants were asked to stare straight ahead and a fixation cross on the screen was provided. We examined the hEOG of 10 participants from this first experiment. While the total number of identified eye movements per minute were fewer, the same significant pattern held, $F(7, 63) = 2.18$, $p < .05$, partial $\eta^2 = .20$ (see Figure 7).

Continuing the third analysis check, we examined the hEOG of 10 participants from the second experiment of Strayer et al. (in press) wherein participants drove a fixed-base high fidelity driving simulator (made by L-3 Communications) with high-resolution displays providing a 180-degree field of view. These participants completed the same eight tasks while driving in a simulated freeway environment. Using the eye movements per minute analysis on this hEOG from the driving simulator, the significant pattern held yet again, $F(7, 63) = 3.44$, $p < .01$, partial $\eta^2 = .28$ (see Figure 8).

We can make several conclusions regarding the pattern discerned in the hEOG from this study. The pattern is not a result of the eye movements per minute analysis because it is also found by examining the spectral characteristics of the signal. Based on covarying the muscle movement recorded by A2, we can determine that this consistent pattern is not purely motor artifact from speaking. However, the pattern is also not purely an effect of cognitive workload. Criticisms against using hEOG in a naturalistic setting due to the increased number of head movements have also been answered: The third analysis check using the hEOG from both the laboratory and the driving simulator experiments resulted in that pattern of increased activity in talking conditions.

Thus, this pattern is not an artifact of the hEOG from the instrumented vehicle because the pattern is found in the driving simulator experiment. It is not an artifact of driving because it is found once again in the laboratory-based experiment where participants who performed the eight tasks were asked to refrain from making eye movements. This pattern is consistently uncovered in each of these analyses. The pattern seems to be something characteristic about the way the eye movements are working that is associated with the tasks, some of which show a pattern linked to the amount of speech production paired with the cognitive workload.

One explanation for these findings is that hEOG could be a reflection of the combined effects of cognitive workload and speech production. Speech production appears to be contributing in an additive manner to an underlying pattern in the hEOG. The addition of speech production is the only consistent difference amongst the conditions that explains the observed pattern. hEOG from tasks with speech production suggests the insertion of additional processes that are affecting the way the eyes are moving. The influence of speech production appears to be independent of the way that the eyes are seen to move in the gaze concentration hypothesis as measured by eye tracking equipment. While a viable explanation, further research examining these Sternberg-like additive processes from speech production on eye movements is merited (cf. Sternberg, 1998). Every analyses presented here converge on a consistent pattern: that eye movement activity as identified in these analyses increases with the amount of speech production performed by the participant.

Table 1
Descriptive Statistics for Eye Movements per Minute

	Mean	SD	SE
Single	39.79	9.55	1.61
Radio	41.35	10.25	1.73
Audiobook	39.20	11.09	1.87
Passenger	67.98	23.20	3.92
Handheld	61.42	20.00	3.38
Handsfree	59.09	16.07	2.72
Text to Speech	55.86	16.61	2.81
OSPAN	46.81	15.02	2.54

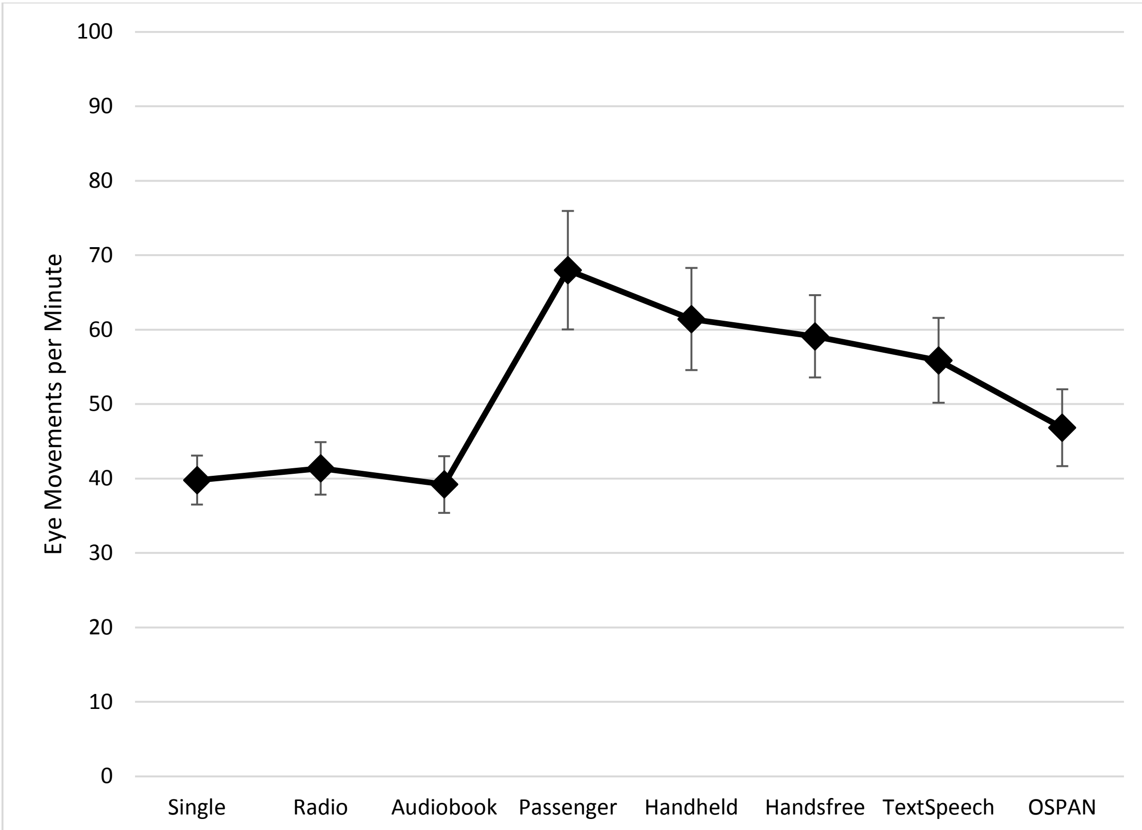

Figure 2. Eye movements per minute. Whiskers indicate 95% confidence intervals.

Table 2

Eye Movements per Minute: Significant Mean Differences

	Radio	Audiobook	Passenger	Handheld	Handsfree	Text to Speech	OSPAN
Single	ns	ns	28.19	21.63	19.30	16.08	7.03
Radio		ns	26.63	20.06	17.74	14.51	5.46
Audiobook			28.78	22.22	19.89	16.67	7.62
Passenger				6.56	8.89	12.12	21.17
Handheld					ns	5.56	14.61
Handsfree						ns	12.28
Text to Speech							9.05

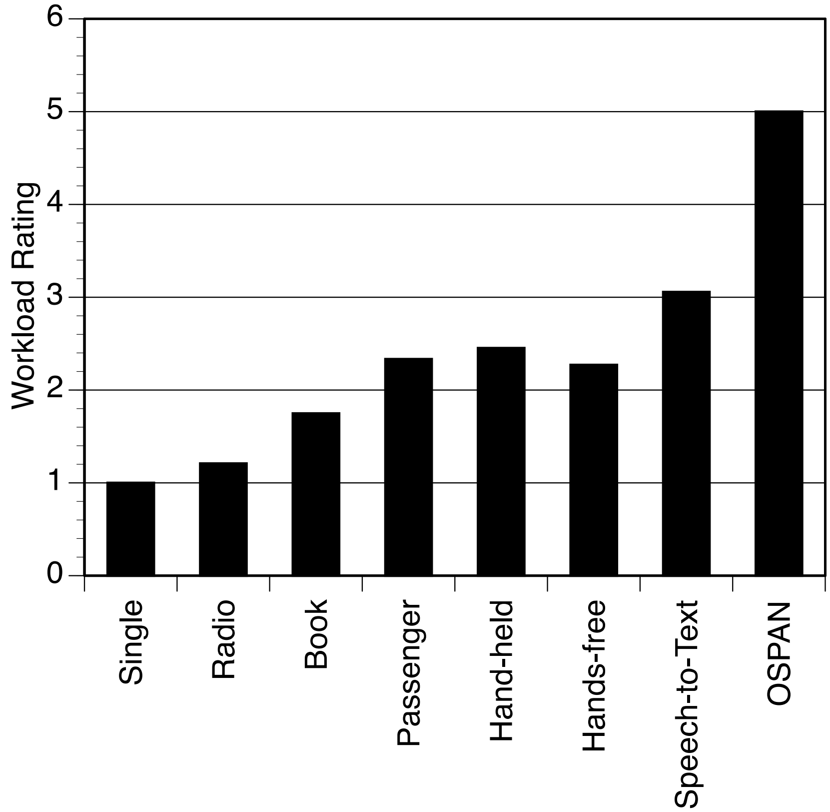

Figure 3. Cognitive distraction scale as assessed by reaction time, driving performance, and subjective ratings.

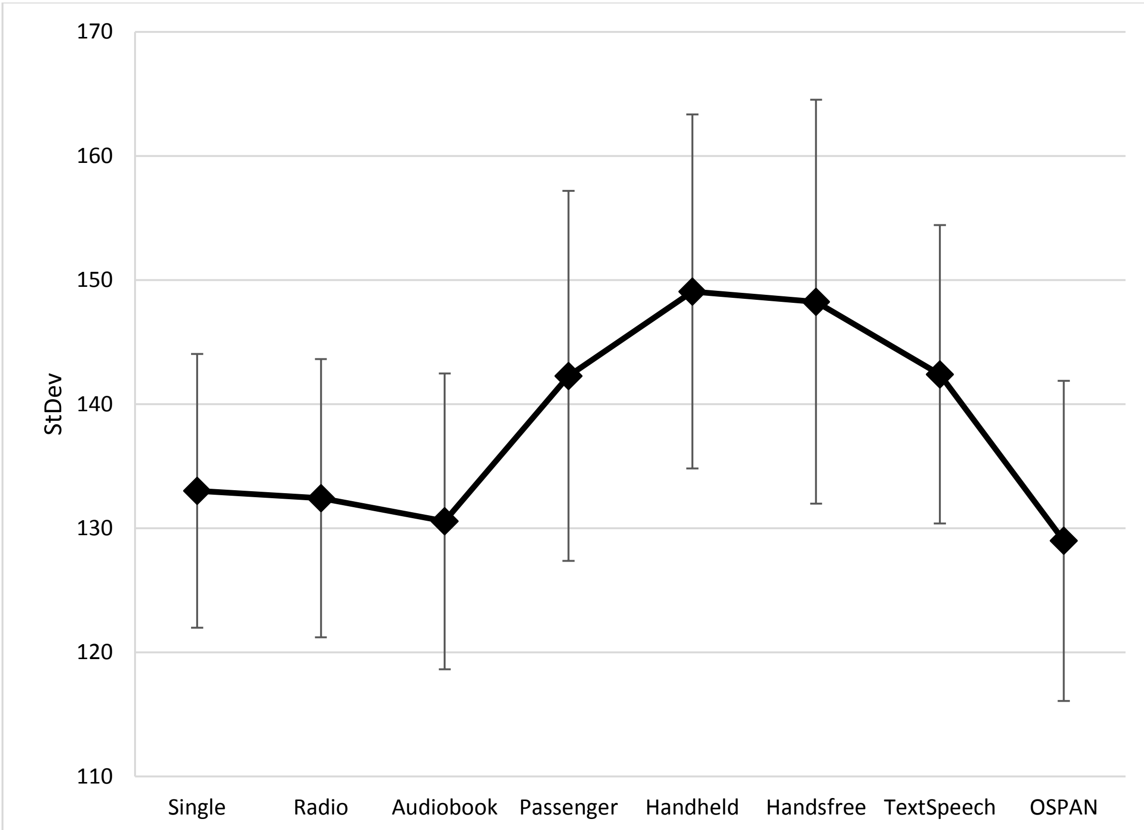

Figure 4. Standard deviation of hEOG. Whiskers indicate 95% confidence intervals.

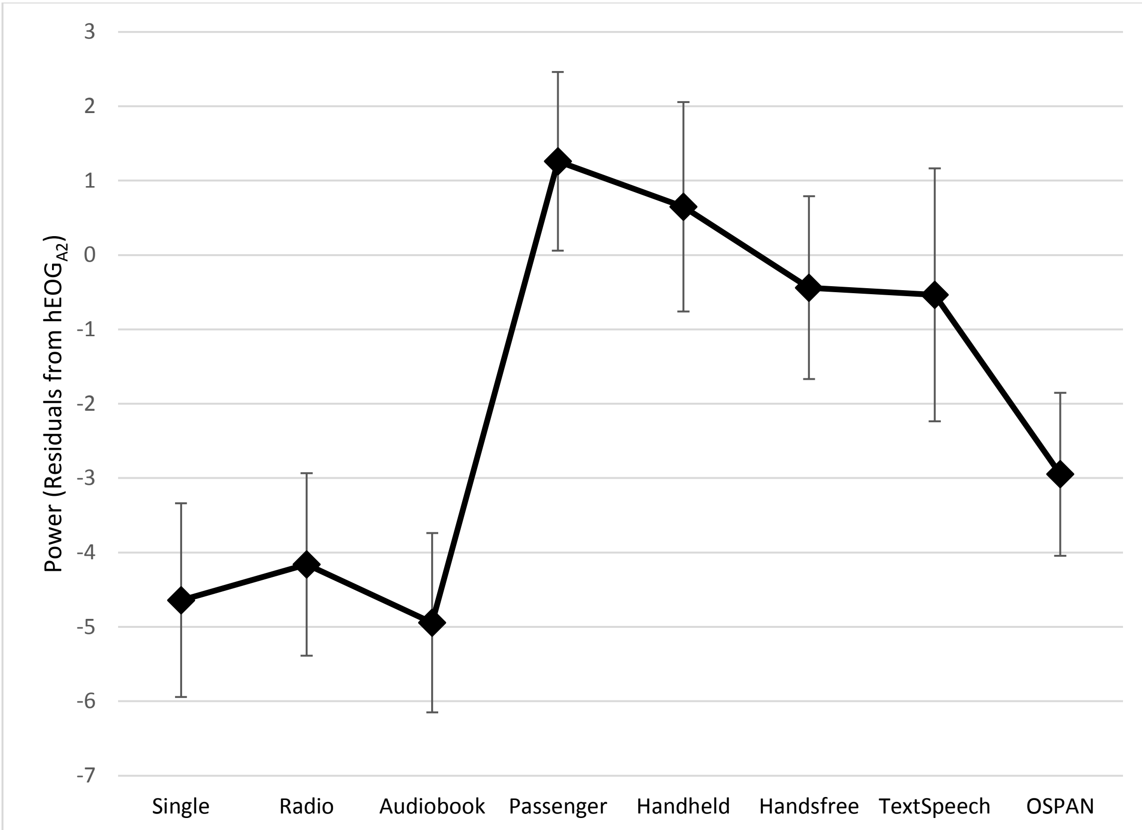

Figure 5. Amount of FFT power for 20-40 Hz range of eye movements. Whiskers indicate 95% confidence intervals.

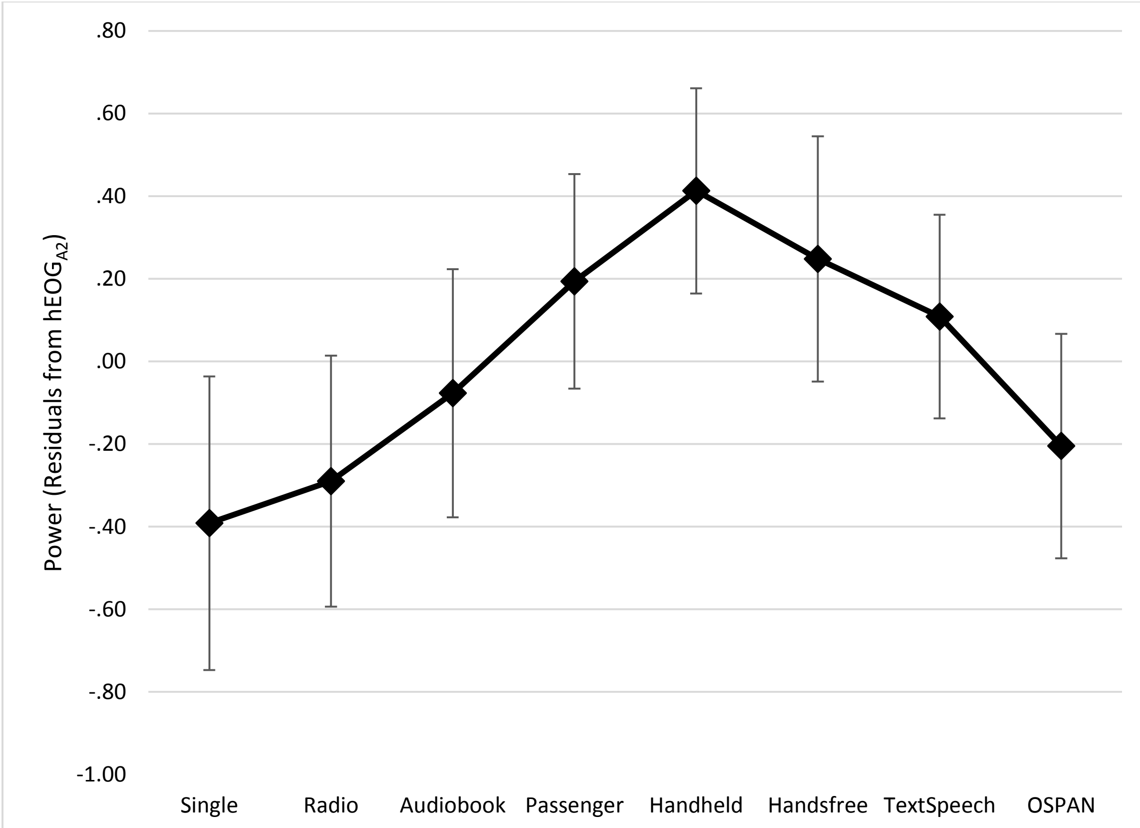

Figure 6. Amount of FFT power for 20-40 Hz range of eye movements covarying A2 mastoid muscle movement. Whiskers indicate 95% confidence intervals.

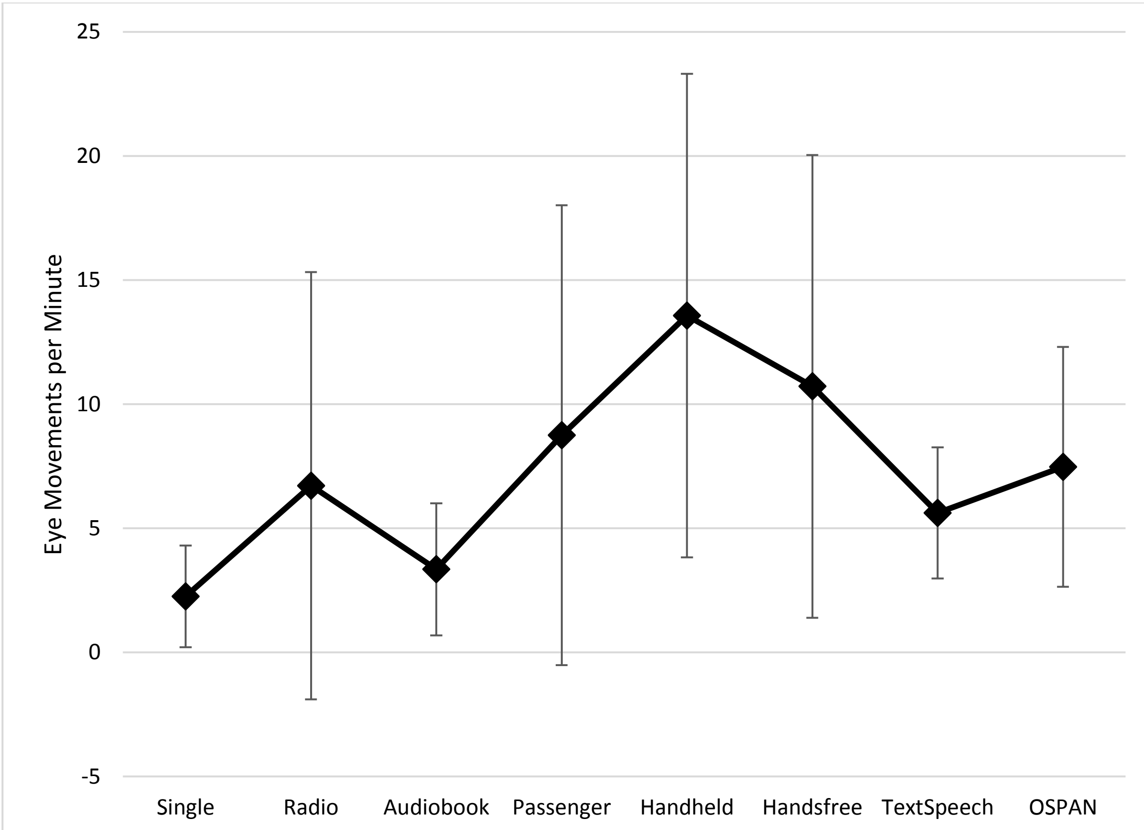

Figure 7. Eye movements per minute for experiment 1, laboratory setting (n = 10). Whiskers indicate 95% confidence intervals.

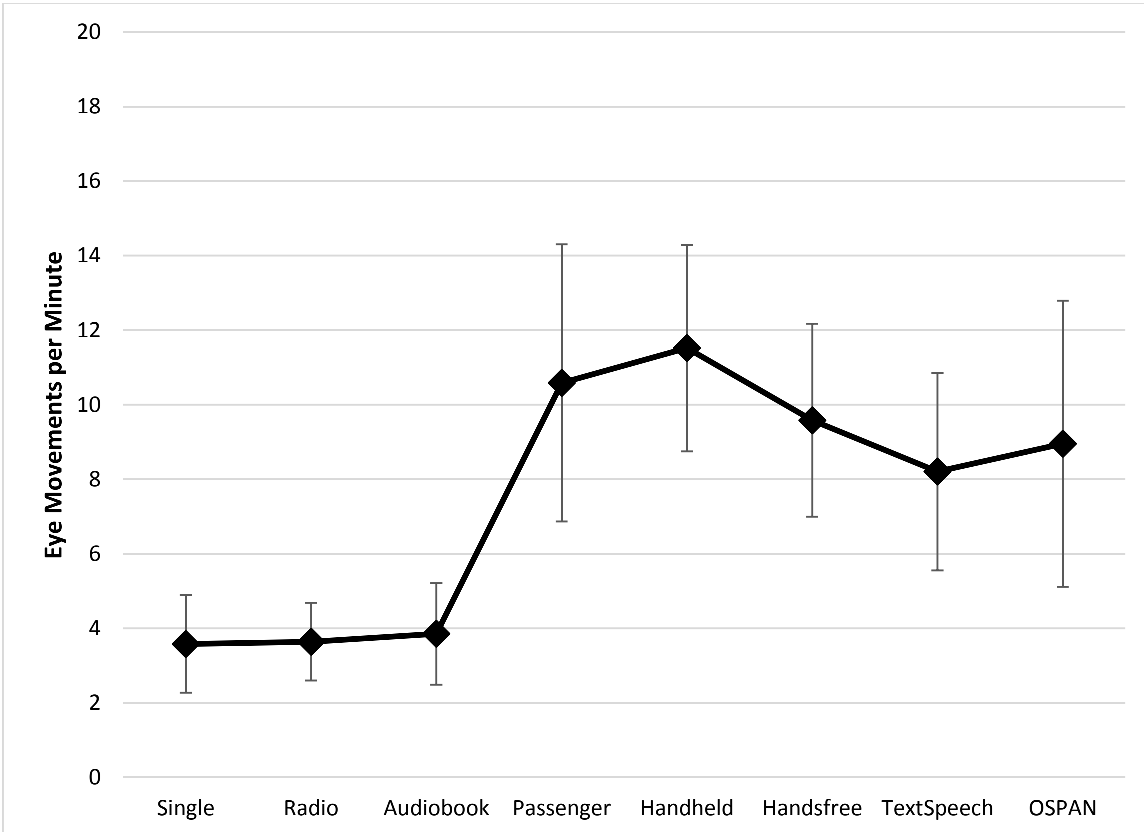

Figure 8. Eye movements per minute for experiment 2, driving simulator setting (n = 10). Whiskers indicated 95% confidence intervals.

DISCUSSION

In light of the wealth of information showing a concentration of gaze under cognitive workload, the application to distracted driving is obvious and concerning. In citing Recarte and Nunes (2000), Hammel and colleagues also found that drivers spend "less time gathering new information" from their driving environment when engaged in "verbal or spatial tasks" whether participants drove in an actual car or in a driving simulator (Hammel, Fisher, & Pradhan, 2002, p. 2175). Speech production tasks provide an increased cognitive workload (Horrey & Wickens, 2004; Recarte & Nunes, 2003), and increased cognitive workload has been linked to concentration of gaze (Harbluk et al., 2007; Reimer et al., 2012). When we talk about cognitive distractions in the vehicle, we are concerned that drivers cease to scan their peripheral environment for unexpected events, such as child chasing a ball into the street. Eye trackers can provide a reliable measurement in simulator studies; however, since eye tracking equipment is notoriously difficult to assess eye movements in a real-world setting, hEOG could be a promising, noninvasive technique to examine a variety of secondary tasks while participants drove an actual vehicle.

In order to narrow our possible interpretations of these hEOG results, we discuss three experimental checks. We were first concerned that participants may have treated the study differently than their own driving, which is a critique often associated with driving simulator studies. However, we assume that participants' perceptions of risk in this study were realistic because the environment entailed driving an actual vehicle in a suburb: the "attentional requirements" (Recarte & Nunes, 2000, p. 32) and consequences were the same that participants' experienced in their own vehicles.

Secondly, based on Strayer et al. (in press), we know that the tasks in this study manipulated cognitive workload as measured by reaction times and subjective ratings, increasing as the task demands required production of speech (Recarte & Nunes, 2003) and greater working memory involvement (see Figure 2). Lastly, time-consuming manual coding of video recordings of participants' eye movements at designated hazard locations showed that participants had significantly lower probabilities of scanning the driving environment under greater cognitive workload (Strayer et al., in press; see Figure 9).

These video coded results match Taylor and colleagues' findings (2013) which measured glance probabilities at hazardous locations in a driving simulator while cognitive workload was manipulated. The Strayer et al. (in press) reduced glance probabilities suggest that gaze concentration was occurring as cognitive workload increased, at least as coded at specified locations throughout the drive. hEOG did not reflect the pattern found in the glance probabilities.

hEOG sought to establish cognitive workload differences via changes in eye movements as a continual effect discernable throughout the entire drive and not just at specific locations that may have exogenously demanded attention (e.g., a changing stoplight). Using hEOG, we were able to detect that there was a significant pattern in eye movement behaviors amongst these conditions; however, this pattern appears to be the result of an additive effect wherein tasks requiring greater speech production, such as found in the conversations, dictating voice to text messages, and in the brief verbal responses to the OSPAN, contribute to greater eye movement activity being identified within the hEOG. While speech production can be used to manipulate cognitive workload, cognitive workload does not place the same demands on hEOG as robustly as speech production. When speech production is a task requirement, using hEOG to measure the cognitive workload associated with dual-task naturalistic driving is not supported as a viable methodology.

The idea that speech production affects the functioning of the visual system as recorded by hEOG should be examined more closely in future research. One possibility arises from the examining the application of hEOG to understanding drivers' behaviors. Tasks that require participants to produce speech affect hEOG differently than "pure" cognitive workload. It is possible that hEOG could be sensitive to tasks that are able to manipulate mental workload while controlling for the additive effect of speech production.

While future work on the "best practices" for the application of hEOG in a natural driving environment are needed, this link on an additive nature between speech production and visual scanning behaviors provides a basis for further research. If individuals are not **S**canning their environment, the remaining processes in SPIDER break down and a driver's situation awareness deteriorates. As auto manufacturers design their in-vehicle infotainment systems to be controlled by speech, the effect that speech production has on safe driving should be considered.

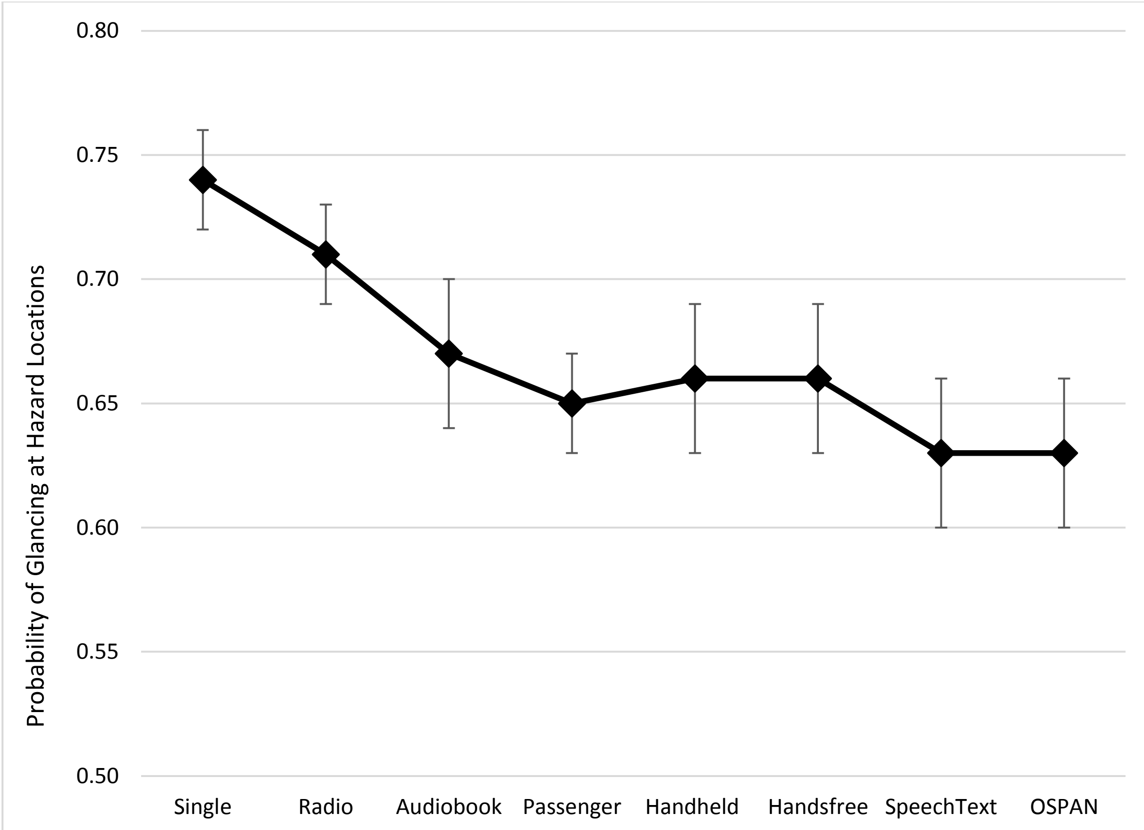

Figure 9. Glance probabilities at hazard locations from video coded eye movements (Strayer, et al., in press). Whiskers indicate standard error of the mean.

REFERENCES

Bergen, B., Medeiros-Ward, N., Wheeler, K., Drews, F., & Strayer, D. (2013). The crosstalk hypothesis: Why language interferes with driving. *Journal of Experimental Psychology. General*, *142*, 119-130. doi:10.1037/a0028428

Bulling, A., Ward, J. A., Gellersen, H., & Troster, G. (2011). Eye movement analysis for activity recognition using electrooculography. *IEEE Transactions on Pattern Analysis & Machine Intelligence*, *33*, 741-753. doi:10.1109/TPAMI.2010.86

Cooper, J. M., Medeiros-Ward, N., & Strayer, D. L. (2013). The impact of eye movements and cognitive workload on lateral position variability in driving. *Human Factors*, *55*, 1001-1014. doi:10.1177/0018720813480177

Cooper, J. M., & Strayer, D. L. (2008). Effects of simulator practice and real-world experience on cell-phone-related driver distraction. *Human Factors, 50,* 893-902.

Dirkin, G. R. (1983). Cognitive tunneling: Use of visual information under stress. *Perceptual and Motor Skills*, *56*, 191-198. doi:10.2466/pms.1983.56.1.191

Dirkin, G.R., & Hancock, P.A. (1985). An attentional view of narrowing: The effect of noise and signal bias on discrimination in the peripheral visual field. In I. D. Brown, R. Goldsmith, K. Coombes, & M. A. Sinclair (Eds.), *Ergonomics International 85: Proceedings of the Ninth Congress of the International Ergonomics Association* (pp. 751-753). Bournemouth, England: Ergonomics International Association.

Drews, F. A., Yazdani, H., Godfrey, C. N., Cooper, J. M., & Strayer, D. L. (2009). Text messaging during simulated driving. *Human Factors*, *51*, 762-770.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science*, *11(1)*, 19-23.

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research: Part F*, *8*, 97-120. doi:10.1016/j.trf.2005.04.012

Fisher, D. G., & Rothkopf, E. Z. (1982). An automated eye movement laboratory for on-line electrooculography. *Behavior Research Methods & Instrumentation*, *14*, 113-120. doi:10.3758/BF03202137

Fisher, D. L., & Strayer, D. L. (2014). Modeling situation awareness and crash risk. Proceedings from State Farm Mutual Automobile Insurance Company: *Engaged Driving Initiative (EDI) Expert Panel*. Washington, D. C.: Association for the Advancement of Automotive Medicine.

Greenberg, J., Tijerina, L., Curry, R., Artz, B., Cathey, L., Grant, P., . . . Blommer, M. (2003). Evaluation of driver distraction using an event detection paradigm. *Journal of the Transportation Research Board*, *1843*, 1–9.

Gruen, S. (2006). *Water for elephants: A novel*. Chapel Hills, NC: Algonquin Books.

Hammel, K. R., Fisher, D. L., & Pradhan, A. K. (2002). Verbal and spatial loading effects on eye movements in driving simulators: A comparison to real world driving. In *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting* (pp. 2174–2178).

Harbluk, J. L., Noy, Y., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis & Prevention*, *39*, 372-379. doi:10.1016/j.aap.2006.08.013

He, J., Becic, E., Lee, Y., & McCarley, J. S. (2011). Mind wandering behind the wheel: Performance and oculomotor correlates. *Human Factors*, *53*, 13-21. doi:10.1177/0018720810391530

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*, 787-795. doi:10.3758/BF03206794

Ishihara, S. (1993). *Ishihara's test for color-blindness*. Tokyo: Kanehara.

Joyce, C. A., Gorodnitsky, I. F., King, J. W., & Kutas, M. (2002). Tracking eye fixations with electroocular and electroencephalographic recordings. *Psychophysiology*, *39*, 607-618. doi:10.1017.S0048577202394113

Koga, K., & Osaka, R. (1983). A comparison of triple recording methods of eye movement. *Japanese Psychological Research*, *25*, 181-190.

Levin, M. (2011). Mixed message? While assailing driving distractions, automakers pack in tempting gadgets. *FairWarning.org*. Retrieved Aug 26, 2012, from http://www.fairwarning.org/2011/09/mixed-message.

Lowry, L. (2002). *The giver*. New York: Laurel Leaf Books.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: MIT Press.

May, J. G., Kennedy, R. S., Williams, M. C., & Dunlap, W. P. (1990). Eye movement indices of mental workload. *Acta Psychologica*, *75(1)*, 75-89. doi:10.1016/0001-6918(90)90067-P

Merino, M., Rivera, O., Gomez, I., Molina, A., & Dorronzoro, E. (2010). A method of EOG signal processing to detect the direction of eye movements. *2010 First International Conference on Sensor Device Technologies and Applications*, 100-105.

Muhrer, E., & Vollrath, M. (2011). The effect of visual and cognitive distraction on driver's anticipation in a simulated car following scenario. *Transportation Research: Part F*, *14*, 555-566. doi:10.1016/j.trf.2011.06.003

National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation (DOT). (2012, September). *Distracted Driving 2010 Traffic Safety Facts Research Note* (Publication Docket No. DOT HS 811 650). Washington, DC: National Center for Statistics and Analysis.

National Highway Traffic Safety Administration (NHTSA), U. S. Department of Transportation (DOT). (2012). *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices* (Publication Docket No. NHTSA-2010-0053). Washington, DC: Federal Register.

Quantitative electroencephalography. (n.d.). Retrieved May 25, 2014 from Wikipedia, The Free Encyclopedia: http://en.wikipedia.org/w/index.php?title=Quantitative_electroencephalography&oldid=585881134

Rantanen, E. M., & Goldberg, J. H. (1999). The effect of mental workload on the visual field size and shape. *Ergonomics*, *42*, 816-834. doi:10.1080/001401399185315

Recarte, M. A., & Nunes, L. M. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of Experimental Psychology: Applied*, *6*, 31–43.

Recarte, M. A., & Nunes, L. M. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied*, *9*, 119-137. doi:10.1037/1076-898X.9.2.119

Regan, M. A., Hallett, C., & Gordon, C. P. (2011). Driver distraction and driver inattention: Definition, relationship and taxonomy. *Accident Analysis & Prevention*, *43*, 1771-1781. doi:10.1016/j.aap.2011.04.008

Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. *Transportation Research Record: Journal of the Transportation Research Board*, *2138*, 13–19.

Reimer, B., Mehler, B., Wang, Y., & Coughlin, J. F. (2012). A field study on the impact of variations in short-term memory demands on drivers' visual attention and driving performance across three age groups. *Human Factors*, *54*, 454-468. doi:10.1177/0018720812437274

Reyes, M. L., & Lee, J. D. (2008). Effects of cognitive load presence and duration on driver eye movements and event detection performance. *Transportation Research: Part F*, *11*, 391-402. doi:10.1016/j.trf.2008.03.004

Rowling, J. K. (1998). *Harry Potter and the sorcerer's stone*. New York: Arthur A. Levine Books.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28*, 1059-1074. doi:10.1068/p2952

Sirevaag, E. J., Kramer, A. F., Wickens, C. D., Reisweber, M., Strayer, D. L., & Grenell, J. H. (1993). Assessment of pilot performance and mental workload in rotary wing aircraft. *Ergonomics*, *9*, 1121-1140.

Sternberg, S. (1998). Discovering mental processing stages: The method of additive factors. In D. Scarborough, S. Sternberg (Eds.), *Methods, models, and conceptual issues: An invitation to cognitive science, Vol. 4* (pp. 703-863). Cambridge, MA, US: The MIT Press.

Strayer, D. L., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors*, *46*, 640-649.

Strayer, D. L., & Drews, F. A. (2007). Cell-phone-induced driver distraction. *Current Directions in Psychological Science*, *16*, 128-131.

Strayer, D.L., Drews, F.A., Albert, R.W., Jonhston, W.A., (2001). Cellphone-induced perceptual impairments during simulated driving. In: *Proceedings of the International Driving Symposium on the Human Factors in Driver Assessment, Training, and Vehicle Design*. Aspen, CO.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied*, *9*(1), 23-32. doi:10.1037/1076-898X.9.1.23

Strayer, D. L., Turrill, J., Cooper, J. M., Coleman, J. R., Medeiros-Ward, N., & Biondi, F. (in press). Assessing cognitive distraction in the automobile. *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

Strayer, D. L., Watson, J. M., & Drews, F. A. (2011). Cognitive distraction while multitasking in the automobile. In B. H. Ross (Ed.), *The psychology of learning and motivation: Advances in research and theory (Vol 54)* (pp. 29-58). San Diego, CA US: Elsevier Academic Press.

Taylor, T. T., Pradhan, A. K., Divekar, G. G., Romoser, M. M., Muttart, J. J., Gomez, R. R., & ... Fisher, D. L. (2013). The view from the road: The contribution of on-road glance-monitoring technologies to understanding driver behavior. *Accident Analysis & Prevention*, *58,* 175-186. doi:10.1016/j.aap.2013.02.008

Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research: Part F*, *8*, 167-190. doi:10.1016/j.trf.2005.04.014

Watson, J. M. & Strayer, D. L. (2010). Supertaskers: Profiles in extraordinary multi-tasking ability. *Psychonomic Bulletin & Review*, *17*, 479-485.

Woestenburg, J. C., Verbaten, M. N., & Slangen, J. L. (1984). Eye-movements in a two-dimensional plane: A method for calibration and analysis using the vertical and horizontal EOG. *Biological Psychology*, *18*, 149-160.